Renewable and Sustainable Energy Reviews 28 (2013) 174–190

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review on physical and performance parameters of heat recovery systems for building applications

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A R T I C L E I N F O

Article history:
Received 28 January 2013
Received in revised form
5 July 2013
Accepted 14 July 2013
Available online 24 August 2013

Keywords:
Heat or energy recovery
Building applications
Physical parameters
Performance parameter
Efficiency

A B S T R A C T

Owing to global energy crisis, various technical strategies are adopted for energy conservation in buildings through energy-efficient technologies. One of the significant ways for this purpose is by installation or usage of heat or energy recovery device which is known as one of main energy-efficient systems that will decrease the power demands of building heating, cooling, air conditioning and ventilation loads. In order to have an insight into existing knowledge leading to understanding of previous works and researches carried out concerning the area, this paper presents and discusses physical and performance parameters of heat recovery unit and the significances of these parameters on operation and efficiency of the system. In addition, areas that have not received much research attention and that warrant future analysis of this technology are also highlighted.

Contents

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http://dx.doi.org/10.1016/j.rser.2013.07.016

Nomenclature

CFD	Computational Fluid Dynamics
H_i	enthalpy of intake air, kg/kg
H_s	enthalpy of supply air, kg/kg
H_r	enthalpy of return air, kg/kg
H_e	enthalpy of exhaust, kg/kg
M_E	mass flow rate of exhaust air stream, kg/s
M_S	mass flow rate of supply air stream, kg/s
M_{min}	mass flow rate (minimum), kg/s
NTU	number of transfer units
T_i	temperature of intake air in, °C
T_r	temperature of return air to heat or energy recovery, °C
T_e	temperature of exhaust air out, °C
T_s	temperature of supply air to room, °C

Symbols

ε_S	sensible efficiency/temperature efficiency, %
ε_L	latent efficiency/moisture efficiency, %
ε_H	enthalpy efficiency, %
ε_{HR}	heat/energy recovery efficiency, %
ε_{NTU}	the effectiveness–NTU method
ω_i	moisture/humidity ratio of intake air, kg/kg
ω_s	moisture/humidity ratio of supply air, kg/kg
ω_r	moisture/humidity ratio of supply return air, kg/kg
ω_e	moisture/humidity ratio of exhaust air, kg/kg

1. Introduction

Over the past 30 years, the world has experienced large increases in energy consumption as a result of economic and population growth. In the context of built environment, literature has proven that buildings are responsible for about 40% of national energy demand in EU [1], 23% in Spain [2], 35.4% in Greece [3], 30% in China [4,5], 41% in US [6], 39% in UK [7,8], 20–40% in developed countries [2] and predicted to increase by 34% in the next 20 years [9]. In Singapore, the use of electricity in buildings constitutes around 16% of national energy demand [10]. Energy demand is also estimated to increase at the rate of 6.3 annually in Malaysia in order to sustain the nation's economic growth [11]. This increasing trend of energy consumption in buildings is contributed in large proportion by building space heating, cooling and ventilation. The International Energy Agency (IEA) estimated that by the year 2030, the consumption of energy sources will increase by 53%, whereby 70% will be derived from developing countries [12]. In relation to this, a study of World Energy Council (WEC) found that without any changes in our current practice, the world energy demand in 2020 would be 50–80% higher than 1990 levels [13].

In order to overcome energy consumption and at the same time to promote energy conservation in buildings, most countries in the world have shown their commitments by setting up new building standard, policies, regulations, recognition and new technologies. For instance, in the EU, the Energy Performance of Building Directive (EPBD) was adopted in December 2002 whilst in the UK, Building Regulations, a standard for limiting heat gains and losses through elements and other parts of the building services, was developed in October 2010. In Japan, Basic Energy Plan (BEP) was adopted in June 2010 which represents the significant statement of Japanese energy policy and energy crisis [14]. National Energy Policy was also formulated in Malaysia in 1979 with the principal energy objectives to ensure efficient, secure and environmentally sustainable supplies of energy, including electricity. Apart from that, in 2009 Malaysian Green Building Index (GBI) was introduced to promote green building design and sustainability in built environment. These policies, standards and rating tools would encourage the building design to adopt energy-efficient building materials, technologies and at the same time ensure that adequate means of ventilation are provided. Thus, in order to maintain good and healthy indoor environment, provide a habitable and comfortable place for human occupation as well as conserve the energy, energy-efficient technologies should be adopted in building services. Therefore, the challenge nowadays is to develop an energy-efficient system which can make a big contribution to CO_2 emission reduction, to fulfill the building code requirements and energy conservation either as an alternative to

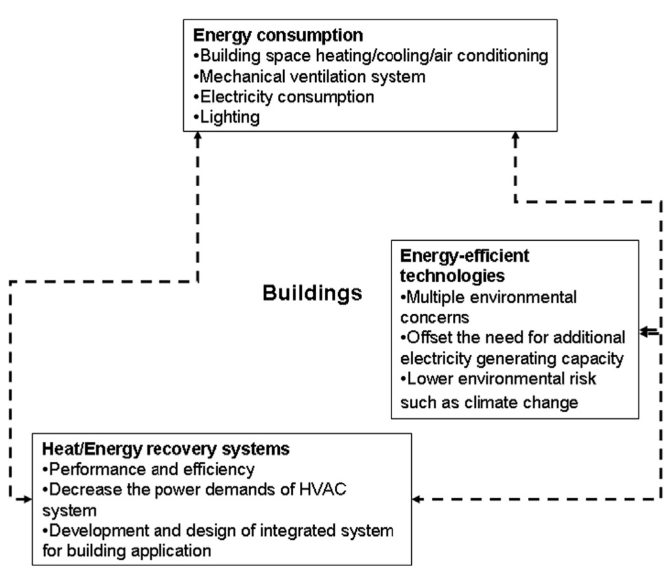

Fig. 1. Link between building and energy and the needs for heat or energy recovery.

the conventional systems or as an incorporating system to the existing technologies. In this approach, one of the significant ways is by installation or usage of heat or energy recovery device which is known as one of the main energy-efficient systems that will decrease the power demands of building heating, cooling, air conditioning and ventilation loads as illustrated in Fig. 1.

As stated by Shurcliff [15], heat or energy recovery is defined as a device that removes in terms of extracts, recovers or salvages heat or mass or energy from one airstream and transfers it to another airstream and is classified into two major categories which are sensible heat recovery [16,17] and latent heat or enthalpy recovery [18–20]. This means that the energy that would otherwise be lost is used to heat the incoming air, helping to maintain a comfortable temperature in a building. In other words, this system introduces mechanisms to recover the "coldness" and/or "hotness" from the exhaust stale air via heat transfer surfaces with the induced fresh air during the ventilation processes. There are many different types of heat or energy recovery systems that are available for transferring energy from the exhaust air to the supply air or vice versa for building applications [21–29] and lots of researches have been conducted in this area to date [30–34]. It is therefore vitally important to know and have an in-depth understanding of this system and its mechanism towards development of energy-efficient technologies. This paper aims to review the system in terms of its physical and performance parameters and the significances of these parameters on the operation and reliability of the system in recovering heat or energy.

2. Physical parameters

Heat or energy recovery system has particular physical components, which makes it unique in its operation and behaviour. The physical conditions and characteristics of the elements that configure the heat recovery determine how it behaves in terms of performance. As discussed in [26], the whole typical heat recovery system is a system comprising of ductworks for inlets and outlets, fans and a core which is a heat exchanger. A basic physical model of heat or energy recovery system as explained by Min and Su [35] is shown in Fig. 2.

Overall, we can differentiate a heat recovery system according to its type, size and configuration/flow arrangement as discussed in [28,36–44]. Specifically, each component of the heat recovery system has its own physical parameters that need to be considered in designing the system. Recently, researchers have produced developments of high interest in heat recovery technologies for building applications. Lots of studies have been conducted to analyse the application and design of the physical model of heat recovery systems. This section highlights the physical parameters

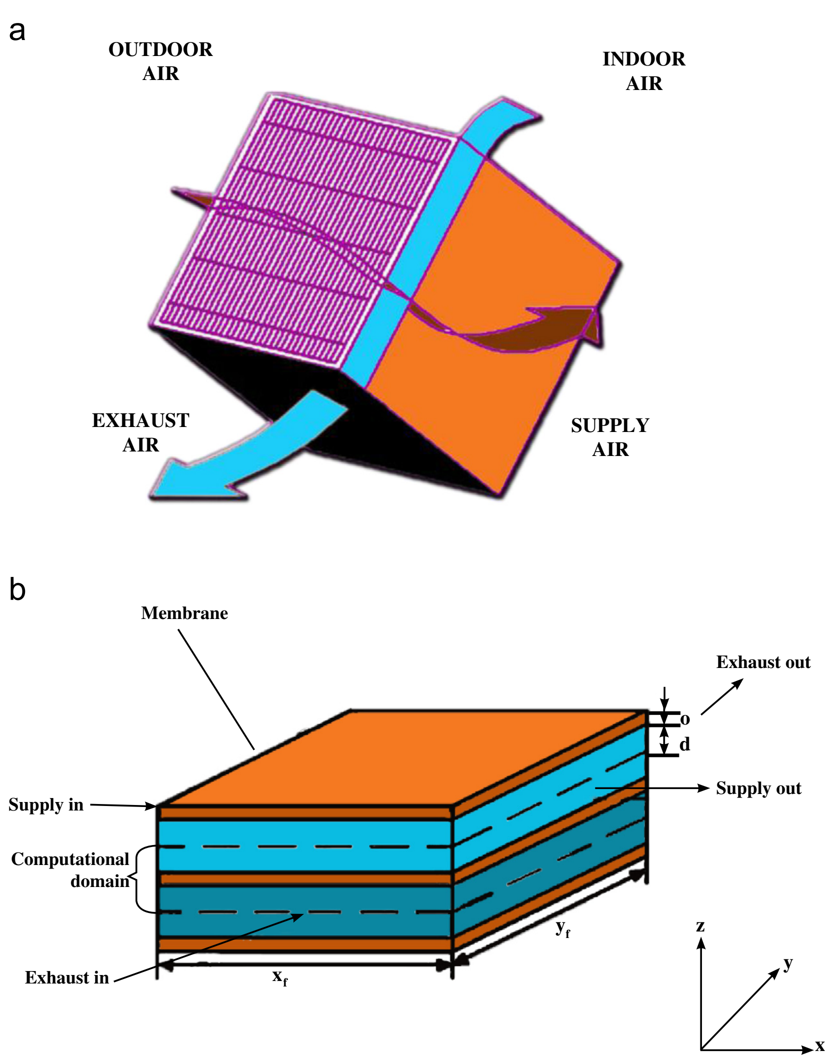

Fig. 2. Basic physical model of heat or energy recovery.
Source: [35].

of heat recovery technologies and their significances on the operation and efficiency of the systems.

2.1. Size and heat transfer area

The heart of heat recovery system is heat exchanger which is the core or a matrix containing the heat transfer area. This heat transfer area is an area of the exchanger core that is in direct contact with fluids and through which heat or energy is transferred. Thus, physical sizes in terms of length, width and height as well as surface area of heat exchanger used in heat recovery system are crucial to the overall efficiency and cost of the system. Generally, by increasing the heat transfer area or size of heat exchanger, the efficiency would also increase but this will add to bulk and cost of the equipment. In order to avoid those weaknesses, optimisation of heat exchanger size for heat recovery application is extremely important. In the literature, several works have been conducted on heat recovery core or heat exchanger [45–48] including efforts on the optimisation of heat exchangers for various heat recovery types [49,50]. For instance, Soylemeyz [51] conducted an optimisation analysis of heat transfer area for three different unmixed type heat exchangers, i.e. counter-flow, parallel-flow and single fluid. In the study, he developed a thermo-economic optimisation analysis for estimating optimum heat transfer area for heat or energy recovery applications. The results illustrated that heat transfer area or size of the heat exchanger affected the effectiveness of heat recovery, which is an important performance indicator of heat or energy recovery system. Scientifically, in the study it was proven that the effectiveness of heat recovery increased as the area increased for three different unmixed type heat exchangers. This was also agreed by Manz and Huber [52] in their study that the area in terms of length of heat exchanger had an impact on the effectiveness (temperature efficiency), whereas in the context of heat pipe recovery unit, size is termed by the number of rows and it has been proven that as the number of row increases, the effectiveness would also increase [53–56]. The logical explanation for this phenomenon is that, with increasing number of rows, the overall heat transfer area is increased, thus increasing the heat transfer between the airflow and heat pipes as stated in Ref. [54]. Meanwhile, in rotary heat recovery, the concern is addressed on the optimum rotary speed to maximise the heat transfer rate per unit of area. Effects of channel wall thickness on heat and moisture transfer were discussed in Ref. [57]. It was proved that there was a strong influence of wall thickness on the system performance and the optimum rotary speed where the higher the thickness, the lower the optimum speed. Numerical optimisation of rotary heat exchanger was then presented in a later study by Dalkilic et al. [58] with the objective to maximise the heat transfer rate of frontal surface area of rotary heat exchanger. Results proved that the flow with the highest heat capacity rate occupied a smaller frontal area. With the capability to transfer both heat and moisture and used for enthalpy recovery [40] nowadays rotary heat exchanger has become one of the successful alternatives to the conventional mechanical dehumidification system for building applications [59].

Besides system efficiency, economy and optimum energy saving are vitally important in considering heat recovery system for building applications [60]. An investigation by Soylemeyz [40] highlighted that the initial and operational cost and net saving of the heat recovery system mainly depend on the size including the dimension of the heat exchanger itself and this indirectly reflects the economics of the heat recovery system. Adamski [61,62] estimated the financial effect due to the use of the heat recovery system instead of a simple ventilation system. On the other hand, Nasif et al. [53] discussed the effect of varying the heat exchanger face area on energy consumption where Kuala Lumpur, Malaysia, weather data were used as a benchmark. The results indicated that as the heat transfer area of exchanger increased, the amount of saved energy increased. Dalkilic et al. [58] approached a new way for determining the area and type of the most appropriate heat recovery core for maximum net gain which was based on a new model. By using the model, they found that the best heat exchanger type and its area can be determined by comparing net gains or effectiveness of heat exchangers at maximum NTU.

Recently, to increase heat transfer area, appendages known as fins have created much attention among researchers in this field which can be intimately connected to the primary surface to provide extended surface of a heat exchanger [63]. The addition of fins reduces thermal resistance on fluid side and thereby increases net heat transfer from the surface. In relation to this, Pongsoi et al. [49], in their work, conducted several experiments on the optimised fin-pitch having a two-row configuration with a size range of 2.4–6.5 mm. From the results, it can be observed that the convective heat transfer coefficient for a fin-pitch of 2.4 mm was relatively low compared with that of other fin-pitches with the same air frontal velocity. This shows that fin-pitch with bigger size gives higher convective heat transfer coefficient which strongly influences the efficiency of heat recovery system in general. On the other hand, Tang et al. [64] investigated the air-side heat transfer of five kinds of fins through both experimental and numerical investigations. Their results indicated that different fins gave different pressure drops and provided different air-side heat transfer performances. Both of these optimised findings are valuable and useful when designing physical model of heat or energy recovery system for building applications.

From the literature, it can be seen that various researches have been conducted in the field of heat recovery since the 1980s [24] in relation to the application, construction, design and efficiency of the systems. Previous researchers have extensively observed the effects of heat transfer area on the effectiveness of various types of heat recovery systems. More recently, major research and development directed at optimisation of heat transfer area have been initiated in order to obtain optimum heat exchanger area for heat or energy recovery applications. Although a great deal of optimisation work has been performed, a gap still exists between research results and practical application. Thus, more future works should be established in this area by taking into account various operating parameters for different climate zones and economic analysis.

2.2. Fans and ducting

Besides the heat exchanger or the core, when designing a heat recovery system, it is also important to take into consideration the size of fan with high energy efficiency as well as the ducting characteristics. In relation to this, an earlier study by Routlet et al. [65] investigated global fan efficiency of heat recovery unit as a function of measured power as shown in Fig. 3 and found that there were significant differences between fans within the same power class used for heat recovery system. These results were also supported by a later research work conducted by Min and Su [35] which found that larger fan power leads to a larger total heat transfer rate, with the maximum total heat transfer rate occurring at a smaller channel height.

Of late, Laverge and Janssen [66] stated that the electric load for fan operation in the heat recovery system used for building ventilation is highly dependent on fan and ducting characteristics. They had conducted a study on primary energy and exergy framework of mechanical ventilation and heat recovery system for different climates in Europe. From their results, it was found that only low specific fan power would make the heat recovery system advantageous if operating energy is concerned. In support

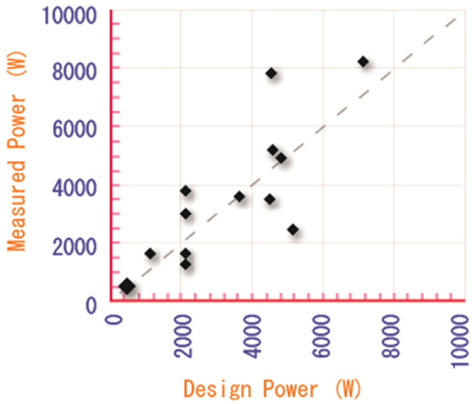

Fig. 3. Global fan efficiency of heat recovery unit.
Source: [65].

of this hypothesis, El-Fouih et al. [33], on the other hand, had carried out a sensitivity analysis by simulation in their study to investigate the influence of exchanger efficiency and specific fan power on the global energy performance of heat recovery system for different types of low energy buildings and different French climate zones. They had analysed the exchanger efficiency and specific fan power by means of a parametric study to test the performance of heat recovery system in function of design options. From the results of the simulation, it was concluded that the fan power of heat recovery system was influenced by three factors: (i) the overall efficiency of the fan; (ii) the resistances in the system (pressure drop); and (iii) the air flow velocity through the unit and ductwork. Aside from various studies for climatic conditions in Europe, there are also several papers that discuss about the performance of heat recovery system and its physical characteristics with regard to primary energy implications in other different climatic conditions [32,67]. In relation to this, Kang et al. [68] carried out an investigation on heat recovery systems with a variable rotational speed fresh air fan to introduce fresh air into the buildings during winter in four cities in different climate zones of China. Their results showed that a variable rotational speed fan with COP value of 2.5 was able to still operate heat recovery system at optimum efficiency and maximum energy saving in most of the selected cities. From these studies, it can be seen that the value of fan COP, which is defined by the ratio of recovered heat and used electrical power indirectly represents the performance of a heat recovery system. In relation to this, Martinez et al. [69] performed an investigation on the COP of a mixed energy recovery by considering fan energy consumption in order to define the relationship between recovered heat flow and energy consumption of energy or heat recovery system. Their results showed that using the COP characteristic as an integrating factor, the optimum results for the mixed recovery system were obtained for the condition of maximum outdoor air temperature with COP value of 9.83.

Furthermore, depending on the size of fan, the size of duct in terms of diameter can be determined for this system for the case where installation of the fan is in the ductwork. As suggested by Shurcliff [15], ducts should be short and free of sharp bends as feasible and of ample diameter in order that the pneumatic resistance will be low and fans or blowers of small, low power, quiet type will suffice. Usually, the air flowing in the ducts is turbulent and the duct length ranges from 3 to 18 m and duct diameters of 0.1–0.2 m are satisfactory, producing pressure drops at a low flow rate [15]. Besides, duct structure and material will also influence flow distribution and are substantial in order to minimise heat loss from the duct system. Otherwise, the heat loss can reduce total efficiency of the system significantly. In addition, duct cross-sections are the predominant factor influencing pressure drop and heat transfer coefficient [70].

In the literature, numerous duct cross-section investigations related to physical characteristics of heat exchanger and heat transfer can be found either experimentally or numerically [71–74]. A study of a prototype unit of duct/heat exchanger for building ventilation was conducted by Manz and Huber [75] by measuring airflow rates, temperatures, air humidity and pressure differences. In the study, the duct/heat exchanger unit for building ventilation was designed to unite two functions in one device: fluid transport and heat recovery. Based on the results, it was observed that using this concept it was possible to realise a heat recovery unit with high-efficiency heat exchange, with temperature efficiency of 0.7 at a duct length of 6 m. Besides, fluid-to-fluid heat transfer in the prototype unit has to be improved by additional fins in the ducting system. Nonetheless, the success of the concept would not only depend on thermodynamic aspects of the duct/heat exchanger unit, but very much on other aspects such as cost-effective production, easy integration into a building and user aspects. In another study, Fernández-Seara et al. [76], quite recently, conducted experimental analyses of an air-to-air heat recovery unit equipped with a sensible polymer plate heat exchanger which was arranged in a parallel triangular duct for balanced ventilation systems in residential buildings to investigate the influence of changing the operating conditions on the heat exchanger performance. The experimental results indicated that the heat transfer rate in the heat exchanger in parallel triangular duct decreased almost linearly as the inlet fresh air temperature increased.

These days, obtaining enhanced heat transfer and reducing equipment cost are two major concerns that need to be satisfied when designing a heat or energy recovery system. To fulfill this demand, Wu et al. [77] presented exergo-economic performance comparison between enhanced heat transfer duct and reference smooth duct subjected to constant wall temperature under various design constraints. From their results, it can be seen that the enhanced duct posed the greatest possibility to be superior to the reference smooth duct under the equivalent pressure drop rather than the other two constraints. More recently, an experimental investigation to determine optimum values of the design parameters of heat exchanger and ducting was described by Taguchi methods in [78].

Since the fan power will typically increase with higher heat recovery efficiency, in order to obtain a system operating at the optimum energy saving, a more complete feasibility evaluation for a specific study should be conducted based on system characteristics and climate data. In addition, the choice between the different physical systems (fans, ducting, filters etc.) including operating costs, building specific characteristics, maintenance costs and component replacement should be considered. Thus for future works, in designing a heat recovery system for building applications, fans and ducting characteristics should be balanced with operating costs and building energy saving.

2.3. Materials and structures

Materials and structures of heat or energy recovery core have evolved along with heat transfer technologies over the past decades. From the engineering approach, materials and structures are selected by how they perform because this will bring some significant effects to their surroundings or how they physically resist the influence of the surroundings. For instance, capillary forces or porosity and pore diameter of the materials play significant roles in moisture transfer. Higher porosity material can hold more transfer and bigger pore diameter has lower mass flow resistance [79]. Besides, thickness of the heat or mass transfer surface heavily affects the heat and mass transfer resistance. On

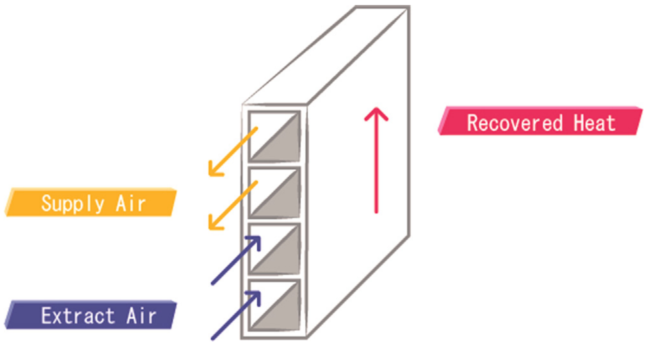

Fig. 4. Segment of an extruded aluminium profile used as a combined duct and heat exchanger.
Source: [52].

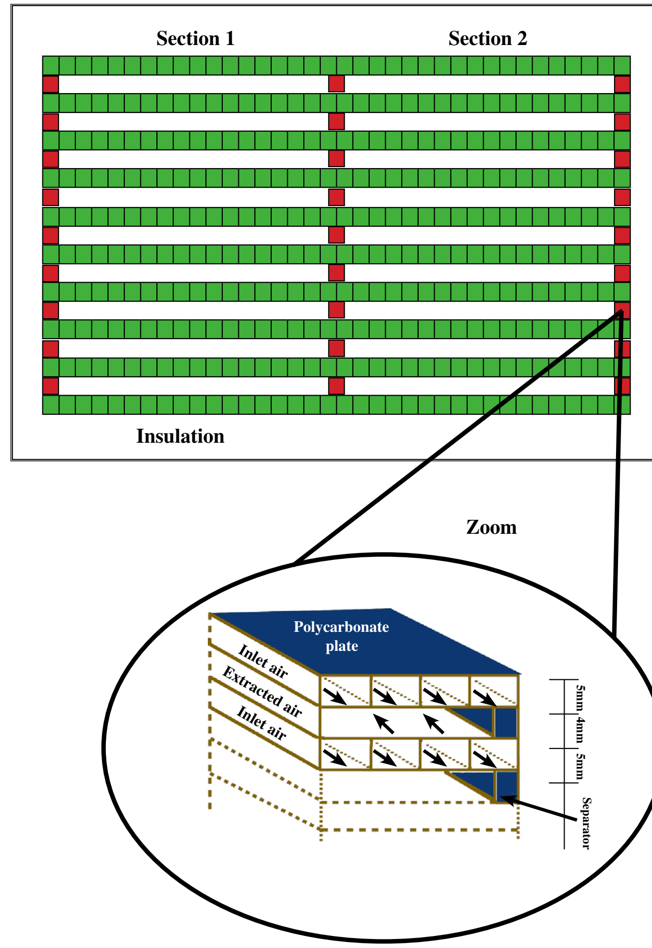

Fig. 5. Horizontal cross-section of the exchanger.
Source: [84].

the other hand, durability of material is another important part to evaluate the optimisation and economic performance of the heat recovery. Up to now, we can observe that lots of research and development efforts on material and structure of heat exchanger or heat recovery core have been performed widely. This section presents several types of material and structure which are commonly used in heat exchanger or recovery core design.

2.3.1. *Metal type*

In the earlier studies, heat exchanger and recovery applications rely heavily on fin-and-tube or plate-fin heat exchanger designs, often constructed using metal type such as copper, aluminium or steel. Using these materials, only sensible heat can be transferred from one stream to other stream neglecting the latent heat. In addition, these materials also have less porosity to retain the condensed moisture from the hot and humid air in heat pipe exchangers. To compete with current market needs, enhancement of the existing metal type should be executed. Thus, to increase the transfer surface, porous structure is considered to replace the smooth surface of the sheet or tube [80] such as wicked metal, foams or wools or fins. From this point of view, Manz and Huber [52] had carried out experimental and numerical investigations on heat recovery (duct/heat exchanger) system by adding aluminium fins on the heat transfer surfaces as shown in Fig. 4. The results showed that by adding the aluminium fins, heat recovery up to 70% at a duct/heat exchanger length of 6 m could be achieved for building ventilation. In another study, the heat pipe recovery consists of 25 copper tubes with the evaporator and condenser sections were finned with 50 square aluminium sheets of 0.5 mm thickness were used in research work by El-Baky and Mohamed [22]. These data denote that aluminium fins are effective transporters of heat from the extract airflow to the supply airflow of heat recovery system. From the literature, it can be concluded that the operating limitations of metal type materials in some applications have created the need to develop appropriate structures to increase heat and mass transfer as well as efficiency of exchanger for heat recovery purpose.

2.3.2. *Polymer-based*

Much of the initial attention in the growth of polymer-based material of heat exchanger or recovery core was motivated by their capability to deal with various fluids, their resistance to fouling and corrosion, and their potential use in integrated heat or energy recovery with humidification and/or dehumidification systems. A thorough review on polymer heat exchangers for heating, ventilation, air-conditioning and recovery has been discussed in T'joen et al. [81]. From the review it can be said that polymer matrix composites do hold promise for use in the design and construction of heat exchangers in heating, ventilation, air-conditioning and recovery applications; however a substantial amount of research is still required into material properties and life-time behaviour. With regard to this, a recent experimental study was conducted by Gendebien et al. [82] on a polystyrene air-to-air heat exchanger with the purpose of gathering performance points. From their work, it was stated that the main disadvantage of polystyrene heat exchangers is related to their low thermal conductivity. This weakness conversely can be counter-balanced by the high enlargement factor which could be attained with polystyrene heat exchangers compared to traditional plate heat exchangers made of metal. Since this new approach is quite new in the field of heat or energy recovery application, further studies should be conducted in this area to investigate design parameters, thermal performance, effectiveness, heat transfer mechanism and effects of operating parameters.

In addition, another famous polymer-based material used in the development of heat exchanger is polycarbonate which is a particular group of thermoplastic polymers that can be easily worked, moulded and thermoformed. Looking at its properties, polycarbonate has good chemical resistance to acids but poor resistance to alkalis and solvents and is able to prevent corrosion. It normally has service temperature ranges from -4 to 135 °C. Because of its low thermal conductivity around 0.19–0.22 W/mK, it finds many applications and it does hold promise for use in the construction of heat exchangers in HVAC and heat recovery applications [81]. For instance, one earlier study of polycarbonate plates in heat exchanger was performed by Kho et al. [83]. Then, after a decade from that study, Kragh et al. [84] conducted performance investigations of a polycarbonate fixed-plate heat exchanger with 0.5 wall thicknesses as shown in Fig. 5 for heat

recovery of mechanical ventilation in arctic climates. Even though polycarbonate plates do have potential in heat or energy recovery application, only few studies can be found in this field in the literature. Thus, more fundamental investigations should be established in this area including numerical analyses, simulation studies as well as experimental works. As a whole, it can be seen that through careful design modification, polymer-based materials have a bright future in heat recovery applications. Thus, future works should look into the emerging technologies of nanoscale polymer-based materials for heat and/or mass transfer.

2.3.3. Fibre

Fibre is one of the common hydrophilic materials that are able to transfer both heat and moisture effectively. Besides its hydrophilic characteristics, it also has lower thermal conductivity. From previous studies, it was found that fibres have much lower thermal conductivity than metals, ranging from 0.01 to 0.3 W/mK [85,86]. In addition, the pore size of various fibres is thin enough to carry the heat or mass transfer with less resistance and has strong absorption ability [87]. However, in terms of hardness, most fibre materials are not strong enough to be used as exchanger plates and the lifespan of the fibre exchanger is short as it is easy to be deformed or damaged when being soaked with water [88].

With regard to the above factors, Liu et al. [89] performed a comparative study of hydrophilic materials including fibres, metals, ceramics, zeolite and carbons for air-to-air heat and mass exchanger. From the study, it was indicated that fibres and carbons were suitable materials for making heat and mass transfer surfaces due to their higher performances. In another study, Dallaire et al. [90] presented a conceptual optimisation of fibre porous core of rotary wheel recovery and they found that the performance of rotary wheel recovery could be drastically improved by properly selecting its thickness and the porosity of the internal thermal mass. On the other hand, an analytical solution for heat mass transfer of heat or energy recovery was studied by Zhang [91] using a hollow fibre with a diameter of 1–3 mm and contact area between the two air streams of 1000 m^2/m^3. Results of the study showed that using this fibre, the heat and moisture exchange effectiveness has the potential to attract commercial interest. Since fibres have the potentials as heat and mass transfer surfaces for heat or energy recovery application, the requirements for economic design, optimisation of operating conditions and enhancement of heat transfer performance investigations are essential for further development of this material. Numerical and experimental investigations as well as CFD simulation involving relevant variables that affect the performance should be established in the future works.

2.3.4. Membrane-based

Nowadays, membrane-based heat exchangers constitute a competitive technology in air-to-air recovery systems mainly due to their high capability as an enthalpy recovery that can simultaneously transfer both sensible and latent heat when compared to other materials [92–95]. Heat exchanger made of vapour permeable membrane such as treated paper or new micro-porous polymeric membrane has the capabilities to transfer both heat and moisture from one airstream to the other, thus providing total energy exchange [35]. Due to these advantages, membrane-based materials have attracted much attention in recent years in the development of heat exchanger for various types of heat or energy recovery [96]. The membrane-based materials can economically achieve high sensible heat recovery and high total energy effectiveness because they have only a primary heat transfer surface area separating the air streams and are therefore not inhibited by the additional secondary resistance inherent in other exchanger types. There are many studies that have been presented in this field over the last decade. Zhang [96] presented a thorough review which covered fundamental and engineering approach on the progress of heat and moisture recovery with membranes. Niu and Zhang [97] performed a theoretical model to evaluate the performance of a membrane-based energy recovery ventilator and investigated the effects of the entrance states of the two airstreams. Zhang and Niu [93] then further developed performance correlations for quick estimation of enthalpy effectiveness of a membrane-based energy recovery ventilator. Min and Su [35] carried out a numerical investigation to study the effects of membrane spacing and membrane thickness. The results indicated that it was necessary to use a thin membrane to obtain a good performance of heat or energy recovery ventilator. Most recently, Woods and Kozubal et al. [94] investigated various support spacers for airflow through membrane-bound channels in energy recovery ventilators to enhance heat and mass transfer.

Due to low latent effectiveness of current enthalpy recovery core [92,98] novel material, the composite supported liquid membrane (CSLM) which used a liquid membrane to selectively transfer moisture was proposed by Zhang [99] in his study. In solving the weaknesses of traditional hygroscopic paper as plate and fin materials, CSLM was used as the plate material. Comparative study was also made between paper-fin and paper-plate, and paper-fin and membrane-plate. Results indicated that the latent effectiveness of the membrane-plate core is 60% higher than the traditional paper-fin and paper-plate core, due to high moisture diffusivity in the CLSM. On the other hand, Zhang and Jiang [100] conducted a study to compare the performance of different core materials and flow arrangements of heat or energy recovery ventilator. Sensible, paper and membrane core with cross and counter-flow were compared and results indicated that the sensible core has the lowest enthalpy effectiveness, while membrane-based core with counter flow arrangement has the best performance. Moreover, a study on steady-state performance of a run-around membrane energy exchanger (RAMEE) for a wide range of outdoor air conditions was presented in Ref. [101]. It was observed that the effectiveness values were significantly dependent on outdoor conditions which results in some effectiveness values exceeding 100% or being less than 0% for several of the outdoor air conditions investigated. Taking into account the results in Ref. [101] and as an enhancement of it, Ge et al. [102] then developed an analytical model for optimisation studies for exchanger size and solution flow rate RAMEE. Results showed that optimisation control of the solution flow rate could enhance annual energy recovery rate up to 7%. Up to date, new approaches for better-designed studies of membrane-based technologies are taking place worldwide. For instance, poly (vinyl chloride)/sodium montmorillonite (Na^+-MMT) hybrid membranes with varied Na^+-MMT content were introduced by Liu et al. 2013 using casting processes for potential use in total heat recovery ventilation systems. Even though this hybrid membrane has high potential applications in heat or energy recovery system, this material still has some defects such as lower water vapour permeability, moisture and enthalpy exchange effectiveness compared to polymeric ionic or cellulose membranes. Therefore further works and deep research in improvement of correlative properties of this material need to be carried out for different types of heat or energy recovery system. From the existing literature, it can be concluded that lots of fundamental works have been carried out. Thus to balance this situation, in the future more cost-effective membranes for energy recovery should be developed with the direction for engineering and commercial applications. Further works should also include studies on the influences of membrane configuration and material properties on the effectiveness, optimisation of heat or energy recovery

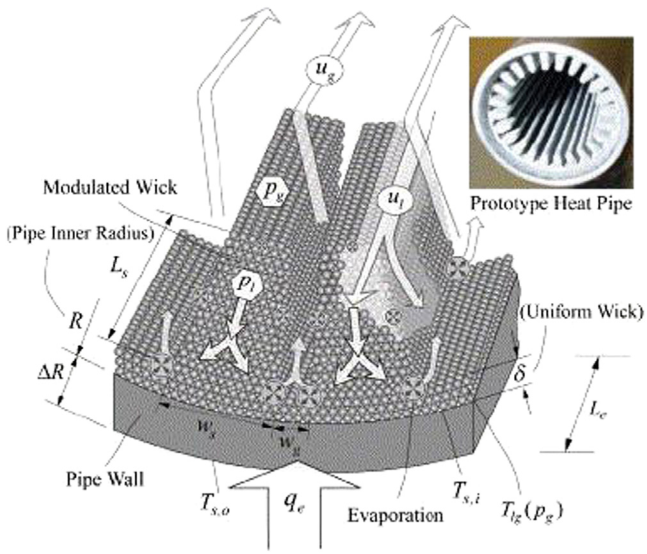

Fig. 6. Schematic of the wick geometry in the evaporator of heat pipe.
Source: [105].

performances and full-scale experimental measurements from the real membrane-based heat or energy recovery system.

2.3.5. Wick and fin structures

In heat exchanger design for heat or energy recovery applications, heat transfer enhancement is one of the major considerations that attracts much attention these days. For this purpose, wick is one of the structures that could increase the heat or mass transfer area and at the same time increase the capillary force of heat exchanger [103]. Wick porosities are enough to contain the condensed moisture in heat pipe exchanger [104]. From this point of view, numerous investigations have been performed with the innovating wick structure in heat pipe exchanger technology in the past. The present wick structure in heat pipe exchanger would result in a larger surface area and would increase the effectiveness as stated by Yau [54]. Fig. 6 shows the wick structure with heat and fluid flow paths in the evaporation surface studied in Ref. [105] where this design was used to increase the performance of heat pipes. Furthermore, a numerical model for transport in flat heat pipe exchanger considering wick microstructure effects was studied by Ranjan et al. [106] using the three-dimensional model. Results showed that the influence of the wick microstructure on evaporation and condensation mass fluxes at the liquid–vapour interface of heat pipe exchanger was accounted for by integrating a microstructure-level evaporation model (micromodel) with the device-level model (macromodel). On the other hand, an experimental investigation on capillary pumped loop with the meshes wick for heat recovery applications in the field of air-conditioning was reported in Ref. [104]. From the results, it was found that the optimal charging rate could be obtained in the range of 70–76% for the given experimental conditions of the proposed capillary pumped loop with the meshes wick and that it was able to perform the heat recovery applications.

Similar to wick, fin structure is attached to the primary surface on one or both fluid sides of heat exchanger to increase the surface area and consequently to increase the total heat transfer rate [94,17,107,108]. As a result of this, recently, lots of studies can be found related to fin structure of heat exchanger in the literature [109]. For instance, a study by Zhang [63] proved that the enhanced heat transfer with fins was useful to overcome major resistance of heat transfer in plate. Recently, Mehrizi et al. [110] highlighted the heat transfer enhancement in a ventilated porous media plate heat exchanger in their works. In addition, effects of fin positions on streamlines, temperature contours, average Nusselt number and outlet mean temperature were also investigated. It was significantly found that the fin position showed a meaningful effect on Nusselt number.

Fins can be of a variety of geometries such as plate-fin and tube-fin and amongst all types of plate-fins, a cross-flow plate-fin structure is the most popular arrangement for the exchanger core due to its compactness and high mechanical strength even with very small channel wall thickness. Since cross-flow plate fin is widely used in the development of heat exchanger, it was optimally designed using multi-objective optimisation technique by Sanaye and Hajabdollahi [111] in their study which also included a sensitivity analysis. The design parameters and fin characteristics were selected such as fin pitch, fin height, fin offset length, cold stream flow length, no-flow length and hot stream flow length. The results revealed that fin pitch, fin height, fin offset length, hot stream flow length and cold stream length (in small effectiveness values) were found to be important design parameters in heat exchangers.

Based on the reviewed literature, it can be concluded that geometries play an important role in heat transfer for heat or energy recovery purpose. Fluid-to-fluid heat transfer in the heat exchanger has improved by additional wicks or fins; however variable wick or fin thicknesses do not substantially improve heat transfer. Besides, to fulfill the better-designed studies of wick and fin structures for energy recovery applications, CFD simulation studies that have been proven as one of the effective approaches for detailed design should be established which could offer a very detailed solution containing local values of all relevant variables that are difficult to measure.

2.3.6. Corrugated structure

Corrugated structures are basic channels construction in fixed-plate exchangers of the heat recovery system [112]. The corrugations force the flow in the plate channels to experience a continuous change in direction and flow area [83]. The benefits of this geometry are that they have efficient heat exchange capabilities and strong mechanical strength, even with very thin material wall thickness. The structure also gives better heat mass transfer [113]. There are a lot of studies in literature that have been conducted to investigate the performance of corrugated structures of heat exchanger's channel such as [114–120]. Islamoglu and Parmaksizoglu [121] suggested that in order to achieve enhanced heat transfer, corrugated structure should be applied in the construction of heat exchanger's channels as shown in Fig.7. Besides, in corrugated structure of heat exchangers and to achieve enhanced heat transfer, various factors such as plate thickness, geometry, plate spacing and plate height that affected the thermal performance need to be considered in the elementary heat exchanger design theory. From this point of view, much attention has been paid concerning this recently. For instance, Doo et al. [123] in their study had used CFD to perform a quantitative assessment of the thermal performance of a cross-corrugated heat exchanger including the longitudinal heat conduction effect for various design options including different plate thicknesses and corrugation geometries for a typical operating condition. Qi et al. [124] proved that thermal performance of the heat exchanger with corrugated louvered fins was affected significantly by flow depth, ratio of fin pitch and fin thickness and the number of the louvers for an optimum design of a heat exchanger. Zhang et al. [125] conducted experimental and theoretical investigations of fluid-side fouling which have been performed inside four corrugated plate heat exchangers with different geometric parameters, such as plate height, plate spacing, and plate angle.

Recently, Woods and Kozubal [122] presented a study on the theoretical pressure drop and heat transfer for an open channel and for simple triangular corrugation (or plan-fin) spacers made of

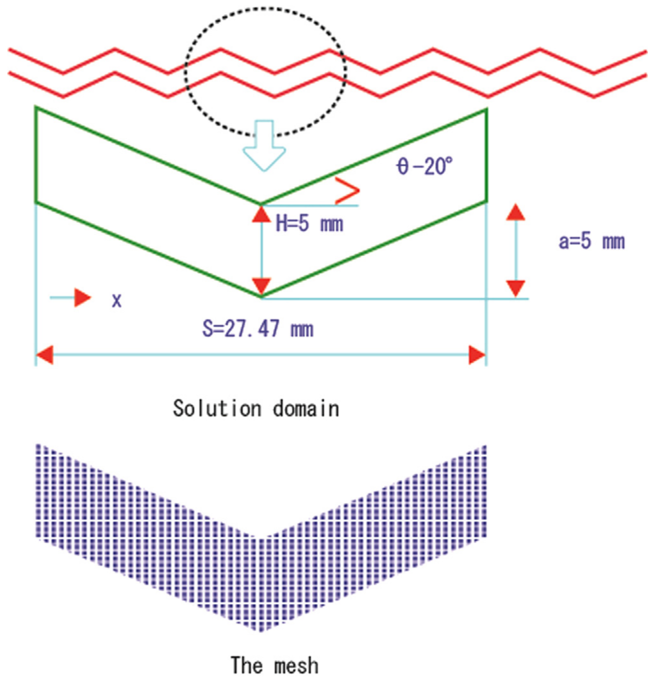

Fig. 7. A schematic representation of corrugated structure channel.
Source: [121].

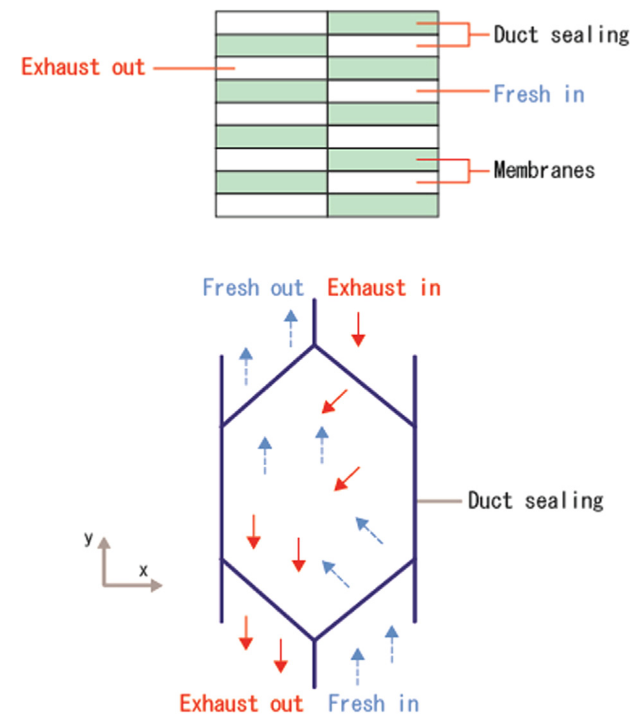

Fig. 8. Schematic of a quasi-counter flow parallel-plates total heat exchanger.
Source: [91].

polypropylene, which is common in heat exchangers and heat recovery systems. In contrast, the effects of channel spacing and phase shift variations on heat transfer and pressure drop in corrugated channels were discussed in Ref. [126] and results of corrugated channels flow showed a significant heat transfer enhancement accompanied by increased pressure drop penalty. Afterwards, Gendebien et al. [82] investigated an air-to-air heat recovery in cross-counterflow arrangement made of several corrugated plates in synthetic material in which the study employed the same ratio of maximum to minimum air flow rate as the one presented by Fernandez-Seara et al. in Ref. [76].

Many theoretical and experimental studies are available in the literature on the corrugated structures. In addition, there are few works reporting on simple geometries of corrugated structures and heat transfer characteristics under different conditions. Further works on more complex corrugation structures should be carried out to better evaluate the convenience of assigning this structure to the heat transfer surfaces. Such studies are useful in understanding and modelling the performance of heat exchangers for heat or energy recovery applications.

2.4. Configurations/flow arrangements

From the literature, it is believed and proved that flow arrangements have direct impact on heat exchanger effectiveness. In addition, heat transfer efficiency is maximised if the two airstreams have opposite directions in airflow arrangement [15]. There are numerous possibilities that exist for airflow arrangement in heat exchanger for heat recovery system. It is well known that effectiveness of a cross-flow heat exchanger is 10% less than that of a counter-flow heat exchanger and the maximum effectiveness is confined to 0.8% [26]. Several research works can be found in the literature from over two decades ago regarding flow arrangement or configuration of heat exchanger or energy recovery core for building applications [41,26,74,84,127,128].

In the earlier study, Kandlikar and Shah [129] analysed several usual configurations and presented guidelines for selecting appropriate flow arrangement from among those considered. It was verified that in most cases symmetric configurations with counter-flow yielded the highest effectiveness. From that point of view, recently Yaici et al. [130] presented a detailed numerical analysis of heat and membrane-based energy recovery ventilators using CFD to investigate the thermal performance of co-current and counter-flow designs under typical summer/winter Canadian conditions. It was found that the numerical results confirmed the superior effectiveness of counter-flow over the co-current flow. These days, major researches directed at optimisation and advanced flow arrangements as these factors are significant in structural design and performance of heat exchanger. For instance, optimisation of the fixed-plate heat exchanger flow arrangement to yield a minimum annual operating cost was studied by Jarzebski and Wardas-Koziel [131]. Pinto and Gut [132] presented an optimisation method for determining the best flow configuration. In relation with advanced flow arrangement, Zhang [91] had developed a mathematical model and experiments of a flow arrangement called quasi-counter flow arrangement (Fig. 8). In the study, he investigated the performance of the system and found that the effectiveness of the arrangement lay between those for cross-flow and counter-flow arrangements. In addition, the comparisons of flow arrangements in case of effectiveness were also studied and it was generally shown that sensible and latent effectiveness values were improved by 5% in quasi-counter flow arrangement. On the other hand, Nasif et al. [53] conducted an investigation of advanced Z-flow configuration heat exchanger which provides counter-flow arrangement over most of the transfer surface to maximise heat and moisture transfer. Afterwards, Al-Waked et al. [133] developed a CFD model which supports conjugate heat and mass transfer problem across the membrane of air-to-air energy recovery heat exchangers that use cross-counter-flow (hybrid-flow) configuration.

From all of these studies, it was proved that the effectiveness of exchanger depends heavily on airflow configurations, conditions and patterns of the supply and exhaust air streams. In addition, the search for new heat exchangers configurations (hybrid or quasi airflow configuration) for heat or energy recovery application

seems to be a very important aspect and future works should be carried out including theoretical, experimental, optimisation, and practical applications as well as optimisation studies.

3. Performance parameters

This section comprises proven techniques of mentoring the performance of heat or energy recovery system in relation to its efficiency or effectiveness from existing established data and previous works in the literature. Efficiency or effectiveness of heat recovery system is usually defined with respect to balanced airflows and the performance of this unit can be studied by a simple mass and energy balance. According to ASHRAE Standard [134], sensible efficiency is expressed by the temperature ratio or temperature efficiency when mass flow rates of supply and exhaust air are equal as shown in

$$\varepsilon_S = \frac{(T_s - T_i)}{(T_r - T_i)} = \frac{(T_r - T_e)}{(T_r - T_i)} = \varepsilon_{S,S'} = \varepsilon_{S,E'} = \varepsilon_S \tag{1}$$

Sensible heat recovery is used where heat transfer without moisture is desired. Enthalpy recovery such as rotary wheel, fixed-plate with membrane based is used to transfer both moisture and heat between air streams [134]. Moisture/latent efficiency is defined as

$$\varepsilon_L = \frac{M_{S'}(\omega_s - \omega_i)}{M_{min}(\omega_r - \omega_i)} = \frac{M_{E'}(\omega_r - \omega_e)}{M_{min}(\omega_r - \omega_i)} \tag{2}$$

When mass flow rates of supply and exhaust air are equal, moisture efficiency is calculated based on the amount of moisture transferred and is presented by

$$\varepsilon_L = \frac{\omega_s - \omega_i}{\omega_r - \omega_i} \tag{3}$$

Enthalpy efficiency or energy efficiency can be defined as

$$\varepsilon_H = \frac{M_{S'}(H_s - H_i)}{M_{min}(H_r - H_i)} = \frac{M_{E'}(H_r - H_e)}{M_{min}(H_r - H_i)} \tag{4}$$

Another way to calculate efficiency was introduced in Ref. [65] by conducting measurements of the heat recovery system as shown in Fig. 9. In the study, they suggested a global efficiency of heat recovery which depends significantly on the air in-filtration and ex-filtration. Based on their study, it was found that by taking the in-filtration and ex-filtration rate, the global heat recovery efficiency was between 60% and 70% for units having 80% nominal heat recovery efficiency. However, the results of their study were only limited to conditions in Switzerland and Germany and thus, more measurements should be conducted in other countries or different climatic conditions in order to get similar information. Afterwards, Jokisalo et al. [135] carried out a study to investigate relation between air tightness of a building envelope, infiltration, and energy use of a typical modern Finnish detached house in the cold climate of Finland using a simple adapted IDA-ICE simulation model and it was found that the average infiltration rate and heat energy use increase almost linearly with the building leakage rate n_{50} in the typical Finnish detached house. From these studies, it can be seen that in-filtration and ex-filtration have significant impact on global efficiency of heat or energy recovery system for building applications. In addition, more studies should be expanded in this area and taking into account the leakage distribution as it has a significant effect on the infiltration rate. In order to have an in-depth understanding about the system, this section presents previous and current works conducted in this area which is related to the performance parameters of heat recovery, their impacts on the system and comparisons to and between previous research and development in this area to date, which includes heat and mass transfer, the effectiveness–NTU method, effects of airflow, effects of temperature, moisture and pressure drop.

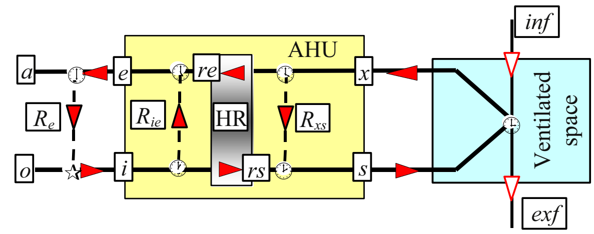

Fig. 9. The tested system of global efficiency study.
Source: [65].

3.1. Heat and mass transfer

There have been numerous investigations of heat and/or mass transfer in heat exchanger for heat or energy recovery application [74,112,100,99,136]. Quite recently, Zhang [91] conducted heat and mass transfer studies of a membrane-based total heat exchanger for heat recovery in air conditioning system. On the other hand, a detailed heat and mass transfer investigation was studied by Zhang and Jiang [100] of a novel porous hydrophilic polymer membrane for two different flow arrangements. The results showed that for the cross-flow arrangement, the membrane was not effectively used either for sensible heat or for moisture transfer as compared to counter-flow arrangement. On the other hand, heat and mass transfer mechanisms in a cross-flow parallel plate membrane-based enthalpy exchanger for heat and moisture transfer recovery from exhaust air streams were numerically investigated by Zhang [74]. It was concluded that the results of the study would give some insight for future applications of heat or energy recovery design. Zhang [63] conducted an experiment to measure the steady heat and mass transfer through the exchanger cores, by the measurements of inlet and outlet temperature, humidity and airflow rates. Results found that the mass transfer resistance for plate was larger than heat transfer resistance, so the humidity changes more slowly than humidity does. In another study, Zhang [96] proposed some novel concepts for heat and moisture transfer analysis in his review on the progress of heat and moisture recovery with membranes. The performance correlations for the effectiveness of heat and moisture transfer processes in an enthalpy exchanger with membrane cores were presented in Ref. [95]. In the study, the total enthalpy effectiveness can be calculated from sensible effectiveness, latent effectiveness and the ratio of latent to sensible energy differences across the unit. Most recently, Woods and Kozubal [122] performed a study on heat and mass transfer enhancement by introducing new corrugated mesh spacers with one spacer in three orientations and comparing it with triangular corrugation spacers. It was found that this new corrugated design could improve heat transfer with little pressure drop penalty compared to the triangular corrugation spacers. For future work, the experimental results from this study can be used to validate a CFD model, which can then be used to investigate spacer-filled channel designs.

3.2. The effectiveness–NTU method

A second definition of efficiency was originally made by Nusselt [137], called number of transfer units (NTU). Method of NTU is based on the fact that the inlet or exit temperature change (difference) of a heat exchanger or heat recovery core is a function of NTU and capacity rate. The NTU is a non-dimensional expression which depends on the heat transfer area and the overall coefficient of heat transfer from fluid to fluid and has been the

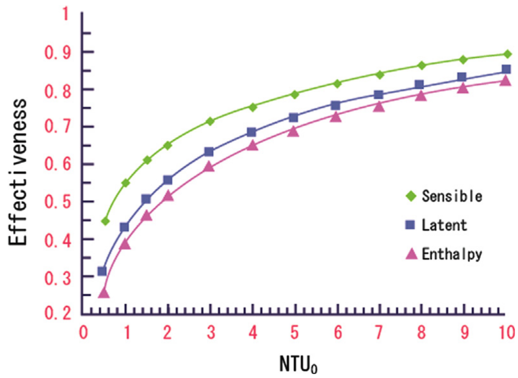

Fig. 10. Effects of total number of heat transfer units on the effectiveness.
Source: [97].

most convenient methodology to predict performance [63]. When the NTU is small the efficiency of heat recovery unit is low, and when the NTU is large the effectiveness approaches asymptotically the limit defined by flow arrangement and thermodynamic considerations. The effectiveness correlations for different types of heat exchangers are discussed in Ref. [72]. Niu and Zhang [97] explained the influence of NTU number on the effectiveness and it was found that the effectiveness increased with increasing NTU number as shown in Fig. 10. It can be seen that the effectiveness increased with increasing NTU number.

In addition, NTU is changed numerically by changing the convective heat transfer coefficients, the transfer area and the mass flow rate of dry air [131]. Thus, the efficiency of heat recovery using the effectiveness–NTU method can be defined with the following equation when the flow arrangement, NTU and the heat transfer ratio are known (Kays and London [138]). For the cross-flow heat recovery, when both air streams are unmixed, $C=0$, the effectiveness is defined as

$$\varepsilon_{NTU} = 1-\exp\{NTU^{0.22}[\exp(-NTU^{0.78})-1]\} \tag{5}$$

For parallel flow heat recovery, the effectiveness is

$$\varepsilon_{NTU} = \frac{1-\exp(-NTU(1+C)}{(1+C)} \tag{6}$$

For counter-flow heat recovery, the effectiveness is as follows:

$$\varepsilon_{NTU} = \frac{1-\exp(-NTU(1-C)}{1-C\exp(-NTU(1-C)} \tag{7}$$

and when $C=1$, the effectiveness is presented as

$$\varepsilon_{NTU} = \frac{NTU}{1+NTU} \tag{8}$$

There are several works conducted in the literature related to the effectiveness–NTU method of heat exchangers. For instance, a study carried out by Zhang and Niu [93] showed that the sensible effectiveness is a function of NTU, the number of transfer units for heat, while the latent effectiveness is a function of NTUL, the number of transfer units for moisture. Nellis and Pfotenhauer [139] performed an analytical study of the effectiveness–NTU relationship for a counter-flow heat exchanger which was subjected to an external heat transfer. On the other hand, Wetter [140] conducted a simple simulation model of air-to-air plate heat exchanger to be used for yearly energy calculations where the effectiveness–NTU relations were used to parameterise the convective heat transfer for a cross-flow with both streams unmixed. Navarro and Gomez [48] conducted a study on the effectiveness–NTU computation with a mathematical model for cross-flow heat exchangers.

Quite recently, Mathew and Hegab [141] conducted a study on application of the effectiveness–NTU relationship to parallel flow microchannel heat exchangers subjected to external heat transfer. In the study he had theoretically analysed thermal performance of parallel flow microchannel heat exchangers and an equation for determining the heat transfer between the fluids was formulated. It was observed that, irrespective of the heat capacity ratio, for a specific NTU, as external heating decreased, the effectiveness of the hot and cold fluids increased. In addition, at a given NTU, reduction in heat capacity ratio improved the effectiveness of the fluids. Thus, it can be concluded that the model developed in Ref. [141] can be used to predict the axial temperature as well as the effectiveness of the fluids in parallel flow microchannel heat exchangers, operating in the laminar flow regime, subjected to external heat flux. However, the model is limited to incompressible and single phase working fluids of microchannel flow applications.

3.3. Effects of airflow

The airflow rate has a significant effect on the efficiency of heat or energy recovery [28]. Shao et al. [56] conducted a study on heat pipe recovery with low pressure loss for natural ventilation and air velocity in the system was measured around 0.5–1 m/s. The results indicated that the heat recovery efficiency decreased with increasing air velocity as shown in Fig. 11. Nasif et al. [53] conducted the experiments of thermal performance of enthalpy or membrane heat exchanger for heat recovery. The measurements were performed for air face velocity ranging from 0.3 to 2.89 m/s. The results discovered that as the air velocities increase, the effectiveness declines as for this range of air velocities the larger the resident time, the higher the heat transfer and effectiveness as shown in Fig. 12.

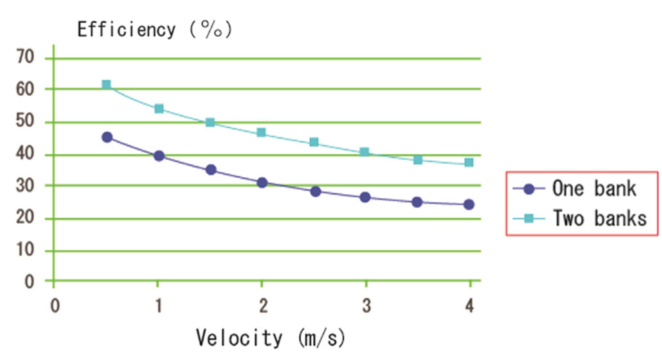

Fig. 11. Heat recovery efficiency of plain fin unit.
Source: [56].

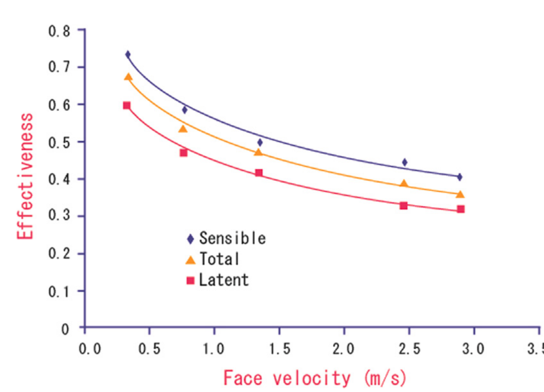

Fig. 12. Experimental sensible, latent and total effectiveness for 60gsm paper heat exchanger.
Source: [53].

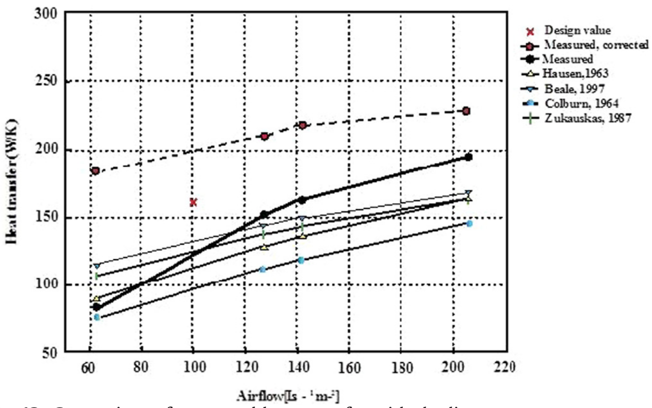

Fig. 13. Comparison of measured heat transfer with the literature.
Source: [142].

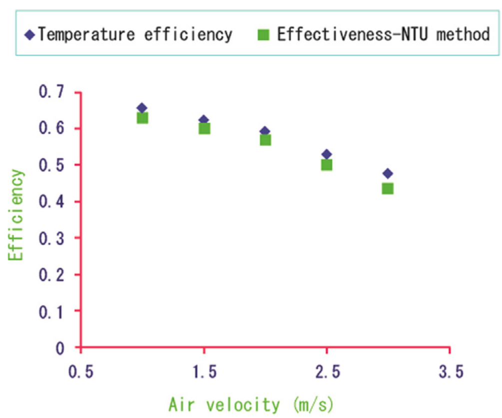

Fig. 14. Efficiency of the heat recovery system.
Source: [28].

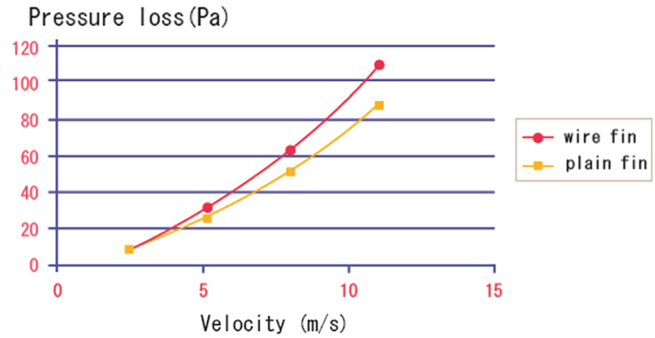

Fig. 15. Pressure loss against velocity.
Source: [56].

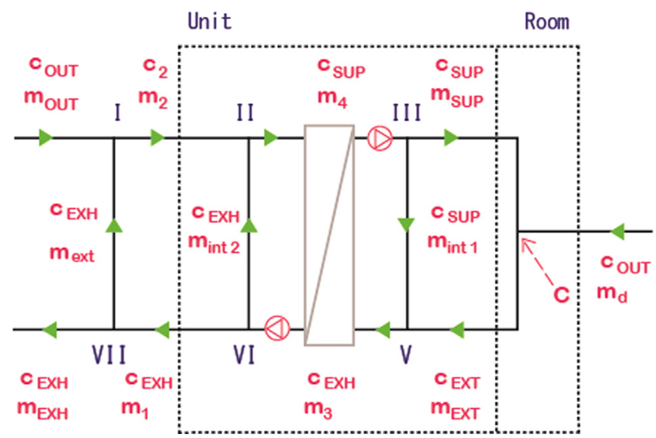

Fig. 16. Main and unintentional air flows in a system consisting of a ventilation unit, room and outdoor space.
Source: [143].

A most recent study by Al-Waked et al. [133] also proved that the effectiveness of the heat exchanger decreased as the airflow rate increased. From their study, it was found that maximum variations of 1.8% and 3.7% in sensible and latent effectiveness, respectively, were noticed when results from their CFD model and results of Zhang [91] are compared. On the other hand, Yaici et al. [130] conducted thermal performance investigation by presenting a detailed numerical analysis of heat and membrane-based energy recovery ventilators using CFD under typical summer and winter Canadian conditions. It was also found that effectiveness of heat recovery decreased with increasing supply/exhaust air velocity.

Contrary to this, heat transfer in terms of heat recovered increased with increasing airflow rates. Hviid and Svendsen [142] compared the heat transfer against airflow rate in their study with several literature sources as shown in Fig. 13. A study conducted in Ref. [28] found that the temperature efficiency and the effectiveness–NTU method decreased as the velocity increased as shown in Fig. 14 and it can be seen in the figure that temperature efficiency is reasonable consistent with the effectiveness–NTU method results. On the other hand, airflows also have significant effects on the pressure loss of heat recovery system. As airflow increases, the pressure loss increases as shown in Fig. 15 [56]. In addition, it has been proven that the temperature of air after the heat recovery unit (supply air to room) varies with air velocity [37].

In a different case, Manz et al. [143] conducted a study to observe the impact of unintentional airflows on the ventilation unit with heat recovery system on the energy requirement for heating. The system studied is shown in Fig. 16. It was found that intentional airflows can considerably reduce the performance of ventilation units in combination with unintentional heat flows through the casing. On the other hand, Woods and Kozubal [122] investigated various support spacers for airflow through membrane-bound channels in heat or energy recovery ventilators to enhance heat and mass transfer. Results showed that unsteady flow occurs in the mesh spacers once a certain flow rate was reached. Lots of numerical, simulation and experimental works can be found in the literature related to effects of airflow on the performance and efficiency of heat or energy recovery system for building applications. However, a gap still exists between these research results and practical application, which mainly lies in the full-scale experimental measurements on real buildings. Further works should be established concerning this area to better evaluate the reliability of this technology in building service sectors.

3.4. Effects of temperature, moisture and pressure drop

In order to determine the sensible and total efficiency, temperature in terms of dry bulb and wet bulb must be known. From a theoretical point of view, the performance of heat recovery system should not be affected by inlet temperatures [34]. For both sensible and total efficiency, the temperature of the inlet air appears to have minor influence [38] in heat recovery system used in natural ventilation system. On the other hand, the effect of heat-pipe inlet temperature was studied by Shao and Riffat [144] for six cases in naturally ventilated buildings and results indicated that the temperature of heat pipe had a small effect on flow loss performance and pressure loss. Min and Su [35] studied the variations of latent-to-sensible heat ratio with outdoor air relative

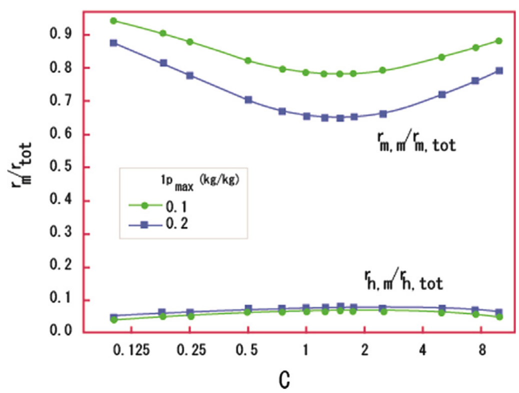

Fig. 17. Variations of latent-to-sensible heat ratio.
Source: [35].

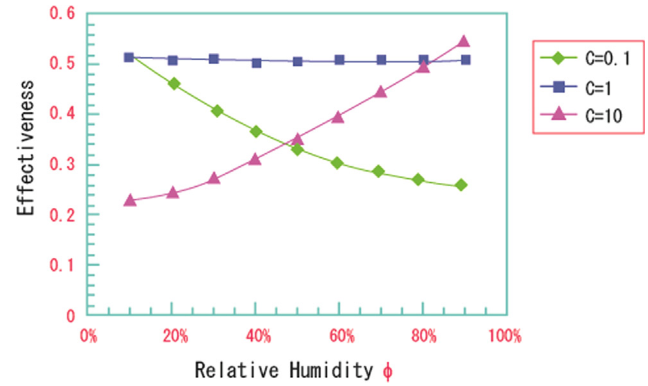

Fig. 19. Effects of relative humidity of supply air on effectiveness with supply in temperature (35 °C).
Source: [97].

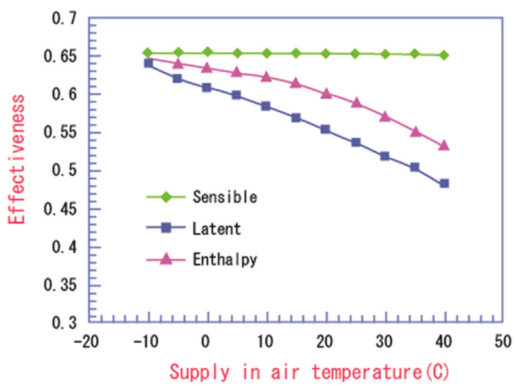

Fig. 18. Effectiveness against inlet temperature.
Source: [97].

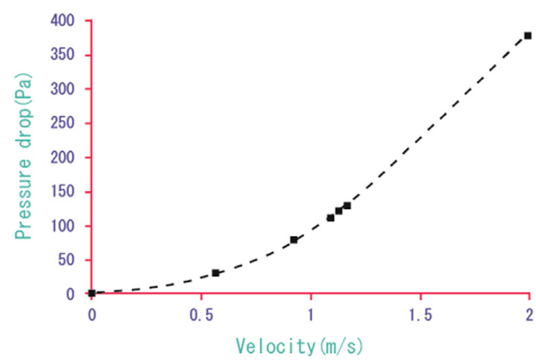

Fig. 20. Pressure drop measurement.
Source: [53].

humidity at three outdoor air temperatures of 32, 35 and 38 °C as shown in Fig. 17. From the study, it was found that for fixed outdoor temperature, as the outdoor humidity increased, the latent-to-sensible heat ratio increased because the latent heat increases. Niu and Zhang [97] investigated the variations of sensible, latent and enthalpy effectiveness against different inlet air temperatures as shown in Fig. 18. From their study, it was found that the sensible effectiveness does not change much with supply air inlet temperature, while the latent effectiveness is very sensitive to temperature and decreased with rising temperatures. In addition, a most recent study by Yaici et al. [130] also indicated that the outdoor temperature and humidity had only minor effects on heat or energy recovery performance.

However, the efficiency of the heat recovery system in real situation varies with the temperature of supply and return air (temperature difference) [145] and because of air leakage, motor heat generation and so on [146]. In the heat recovery system used to recover energy in air conditioning, El-Baky and Mohamed [22] proved that the inlet fresh air temperature is the dominant parameter to enhance the heat transfer rate in the evaporator side of the heat pipe recovery and the effectiveness is increased with increasing inlet fresh air temperature. Mardiana and Riffat [28] investigated the impact of temperature difference on the energy recovered of a heat or energy recovery system. From their study, it was found that maximum sensible recovered energy of 134 W was calculated at 4.3 °C temperature difference across the heat recovery unit at 3.0 m/s air velocity, whilst, the highest latent recovered energy of 32.6 W was achieved at the same air velocity and temperature difference across the heat recovery unit.

Effect of supply air humidity was studied in Ref. [97] and it was found that the supply air humidity has slight effects on the sensible efficiency but it has a major influence on the latent effectiveness as shown in Fig. 19. In addition, moisture diffusivity in membrane core of heat or energy recovery system is a key parameter influencing system performance [147,98]. An investigation in Ref. [35] also claimed that with increasing outdoor humidity, the latent-to-sensible heat ratio increases rapidly, so the enthalpy effectiveness changes from near the sensible effectiveness toward the latent effectiveness.

Experimental measurements of pressure losses across heat pipe recovery unit were carried out in Ref. [56]. The results show that, the pressure loss coefficient reduced as velocity increased. In another study, pressure drop across the membrane-based heat exchanger for energy recovery was measured in Ref. [53]. The results indicated that pressure drop was proportional to the air velocity as shown in Fig. 20. Manz and Huber [52] conducted an investigation of pressure drop in the heat exchanger of heat recovery system by calculating the friction factor as a function of Reynolds number as shown in Fig. 21. From their study, it was found that pressure drop increased with increasing airflow rates. From the existing works, it can be seen that a considerable database already exists for various operating parameters in terms of temperature, humidity and pressure drop and their effect on the effectiveness of heat or energy recovery in which most of these data are based on laboratory conditions and CFD simulation studies. Thus, further works are needed on practical applications in different climatic conditions especially in hot–humid regions.

4. Conclusion

Throughout the literature, it can be seen that there are several parameters that influence the efficiency of effectiveness of heat or

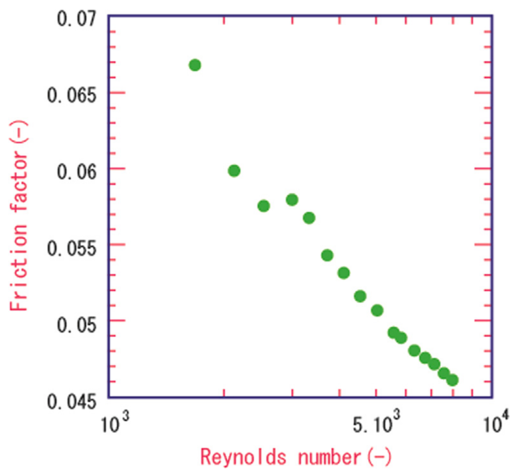

Fig. 21. Friction factor against Reynolds number of a heat recovery system.
Source: [52].

energy recovery systems for building applications. These parameters can be categorised into physical and performance parameters. It was clearly discussed that in order to study the performance in terms of efficiency of heat or energy recovery system, either sensible or enthalpy, the main parameters that should be emphasised are (i) size, structure and material of heat recovery core (heat exchanger); (ii) size of ducts and fans; (iii) configuration or flow arrangement; (iv) heat and mass transfer; (v) flow and pressure drop in the ducts; (vi) temperature and humidity and (vii) airflow rates. It was proven that the efficiency or effectiveness of heat recovery increases as the area increases. Flow arrangements have direct impact on heat exchanger effectiveness and heat transfer efficiency is maximised if two airstreams have opposite directions in airflow arrangement. Besides, the selection of fan and size of duct should be considered in designing heat or energy recovery system for building applications as these components are significant to the performance of the system. In addition, duct structure and material will influence the flow distribution and are also substantial in order to minimise heat loss from the duct system. Otherwise, the heat loss can reduce the total efficiency of the system significantly. Furthermore, material and structure of heat exchanger are the predominant factors of heat and mass transfer. Recently, membrane-based materials constitute a competitive technology in heat or energy recovery systems due to their high capability to transfer both heat and moisture simultaneously.

Heat recovery efficiency can be determined by application of three suggested methods as follows:

(i) The ASHRAE standard method which can be defined in terms of sensible/temperature efficiency, latent efficiency and enthalpy (total) efficiency.
(ii) The effectiveness–NTU method which can be defined by the calculation of NTU and heat capacity ratio, C, when flow arrangement is known.
(iii) Global efficiency which takes into account the ex-filtration and in-filtration rate in the ventilation system.

In any heat recovery system, reducing airflow rates always increases efficiency. On the other hand, airflows have significant effects on all types of heat recovery efficiency, pressure loss and transferred (recovered) heat or mass. For both sensible and total efficiency, the temperature of the inlet air appears to have minor influence in the heat recovery system. However, the efficiency of the heat recovery system in real situation varies with the temperature of supply and return air (temperature difference). In addition, the temperature change increases with increasing inlet fresh air temperature. Thus, as a conclusion, performance and efficiency of heat or energy recovery system are related to the ambient climatic conditions and operating parameters in terms of temperature and relative humidity, effects of airflows, pressure drop and fan power. Therefore, to improve the performance of heat or energy recovery system, more efficient heat transfer materials, structures and more efficient fans must be explored. In addition, more future works and optimisation study should be established concerning the physical and performance parameters of heat or energy recovery to better evaluate the reliability of this technology for building applications.

Acknowledgements

We wish to express our acknowledgements to FRGS Grant (203/PTEKIND/6711274), Ministry of Higher Education of Malaysia (MOHE), USM Short Term Grant (304/PTEKIND/6312055) and Industry Funding United Kingdom for the financial supports associated with this study.

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